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EM Radiation

- While Faraday speculated that 'light' had something to do with electricity and magnetism, Maxwell was the first to show that light is an **oscillation of an eletromagnetic field**

  Maxwell's theories allowed him to predict the following:

  - EM waves can exist at any frequency, not just visible light (we'll come back to the EM spectrum shortly)

  - An EM wave can travel in vacuum (i.e. a source-free region of space that contains neither charge nor magnetic particles)

    → physically, this indicates the 'fields' are real things (not just pictures/lines that inform us about what something 'would' do)

  - The two fields can exist in a **self-sustaining** fashion: a changing magnetic field creates an electric field (Faraday's Law) that in turn changes in such a way to re-create the original magnetic field (Ampère-Maxwell Law)

  - All EM waves travel in vaccum w/ the same speed (i.e. the **speed of light**)

- In vacuum, we can write the four source-free versions of Maxwell's eqns.:

  1) $\oint \bar{E} \cdot d\bar{A} = 0$ (Gauss' Law, w/ no charge)

  2) $\oint \bar{B} \cdot dA = 0$ (no magnetic monopoles)

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3) $\oint \bar{E} \cdot d\bar{s} = -\dfrac{d\Phi_m}{dt}$ (Faraday's Law)

4) $\oint \bar{B} \cdot d\bar{s} = \epsilon_0 \mu_0 \dfrac{d\Phi_E}{dt}$ (Ampère-Maxwell Law)

Finding a general solution to these eqns. is beyond the scope of 1410 mathematically (you'd do this in a 2nd or 3rd year physics course), but suffice to say that for an electromagnetic wave propagating along $\hat{x}$, one possible solution is

$$\bar{E} = E_0 \sin\left[2\pi\left(\frac{x}{\lambda} - ft\right)\right]\hat{y}$$

$$\bar{B} = B_0 \sin\left[2\pi\left(\frac{x}{\lambda} - ft\right)\right]\hat{z}$$

$\bar{E}$ and $\bar{B}$ just oscillate w/ respect to space and time
→ <u>waves</u>

→ since these expressions must be consistent w/ Maxwell's eqns., it follows that

$$E_0 = \frac{B_0}{\epsilon_0 \mu_0 \lambda f} = c B_0$$ where $c = \lambda f$
(phase velocity; see 3/25 notes)

where $c = \dfrac{1}{\sqrt{\epsilon_0 \mu_0}} = 3.00 \times 10^8$ m/s
(speed of light!)

<u>Note</u>: No other wave speed satisfies Maxwell's eqns., so <u>ALL</u> EM waves must move at this speed (regardless of frequency)

- Light can also travel through non-vacuum (e.g. air, water), but there will be slightly larger permitivity (ϵ) and permeability (μ_0) meaning EM waves will travel a bit slower
  → speed of light in vacuum is the 'ceiling'

- Waves transfer energy and EM waves are no exception.
In a nutshell, the **intensity** [J/s], defined as power per unit area, is given by:

$$I = \frac{c\epsilon_0}{2} E_0^2 \longrightarrow I \propto E_0^2$$

Also as a reminder from the 3/27 notes, for a source that emits EM waves in a **spherically symmetric** fashion (think cell phone tower), the intensity at some radial distance r from the source is given by

$$I = \frac{P_{source}}{4\pi r^2} \longrightarrow I \propto \frac{1}{r^2}$$

(P_{source} is the power of the source)

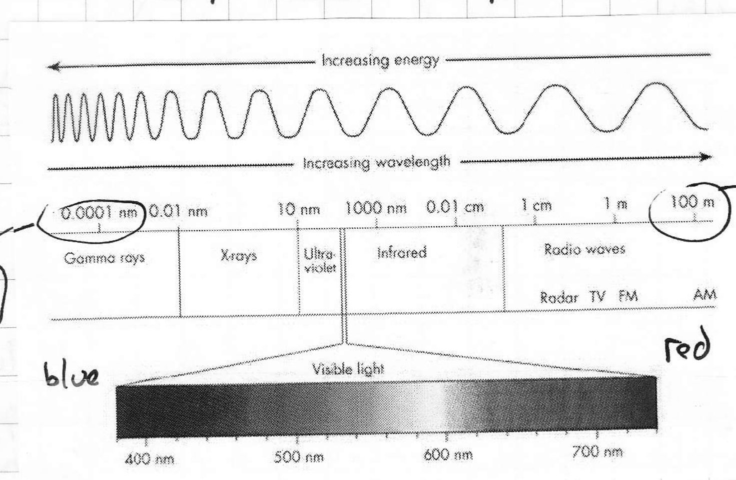
EM spectrum

- A lot of everyday 'signals' come in the form of EM radiation spanning the spectrum (remember $c = \lambda f$ and c is a const., so λ and f are not mutually exclusive!)

- Visible light is just one small portion of the spectrum

- Radio waves are very useful in a lot of modern technology (e.g. wifi and cell phone signals are ~ GHz)

$\boxed{f \sim 10^{21}\ Hz}$



$\boxed{f \sim 10^{6}\ Hz}$

NOTE: giga $= 10^9$, mega $= 10^6$

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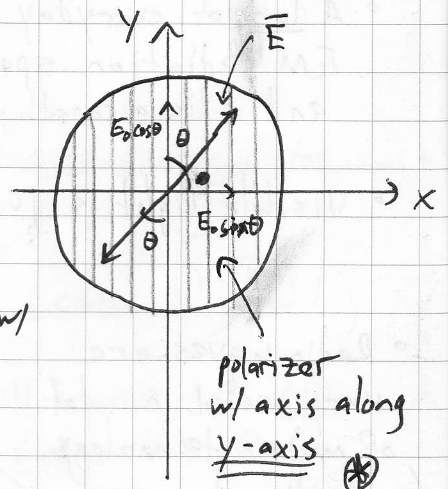
Polarization

- As light propagates, though $\bar{E}$ is perpendicular to the direction of propagation, there is still a continuum of possible directions $\bar{E}$ can take (think of rotating around a circle)

- the **plane of polarization** for EM waves is defined as the plane containing $\bar{E}$ and the propagation direction $\bar{S}$
  ($\bar{S} \equiv \frac{1}{\mu_0} \bar{E} \times \bar{B}$, this is called the Poynting vector)

NOTE: Longitudinal waves (e.g. sound) cannot to polarized, only 2-D (or higher dimensional) transverse waves

- A **polarizer** is an object through which an EM wave can pass and attenuates components of the wave whose plane of polarization is not aligned w/ the polarizer's axis
  (see Giordano fig. 23.24 - 23.27)



$$\bar{E}_{incident} = \underbrace{E_{\perp} \hat{x}}_{\text{perpendicular to axis of polarizer}} + \underbrace{E_{\parallel} \hat{y}}_{\text{parallel (i.e. in line) w/ polarizer}}$$

θ - angle between incident plane of polarization and polarizer's axis

$$\bar{E}_{transmitted} = E_{\parallel} \hat{y} = E_0 \cos\theta$$

$\rightarrow$ $I_{transmitted} = I_0 \cos^2\theta$ (Malus' Law) (since $I \propto E^2$)

- Sometimes useful to think of a polarizer in analogy to a **picket fence**: long vertical slots but narrow horizontal spacing

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- Sunlight is unpolarized and a polarizer (e.g. sunglasses whose lens are polarized) can help reduce intensity to your eyes without a noticeable change

ex to make the change due to polarized sunglasses apparent, 'stack' them (i.e. take two lens and rotate them relative to one another while looking at something bright through both lens)
→ this is a good way to test if both are polarized (as rotating won't do anything if one or both are unpolarized)

Wave - Particle Duality

- A very deep concept in modern physics is the notion/observation that light behaves in such a way that it exhibits properties of both a particle and a wave → paradox?

- Einstein made a big breakthrough in 1905 (one of many) when he proposed that EM radiation is not a wave per se, but a 'small packet' of energy (which he called a 'light quantum') with energy

$$E = hf = h\frac{c}{\lambda} \qquad [h = 6.63 \times 10^{-34}\ \mathrm{J \cdot s}\ \text{Planck's constant}]$$

The notion of a 'light quantum' was later renamed a **photon**

NOTE: Einstein used this idea to explain an experiment called the **photoelectric effect**, for which he was later awarded the Nobel Prize in 1921 (and really opened up a new branch of physics called **quantum mechanics**)